Final Technical Report (FTR)

Earthquake Hazards Program Assistance Awards

July 13, 2020

- USGS Award Number: G18AP00035
- Title of award: Advancement of the ISC-GEM Global Instrumental Earthquake Catalogue, 1904-2018 (Years 1-2)
- Author(s) and Affiliation(s): Dmitry A. Storchak, International Seismological Centre, Pipers Lane, Thatcham, Berkshire, RG19 4NS, United Kingdom, Phone: +44 1635 861022, Fax: +44 1635 872351, dmitry@isc.ac.uk
- Term covered by the award: 06/22/2018 through 06/21/2020
- Acknowledgement of Support and Disclaimer

This material is based upon work supported by the U.S. Geological Survey under Grant No. **G18AP00035**.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey.

• Abstract

The ISC-GEM catalogue is unique as it answers specific needs of seismic hazard research. It provides long-term, uninterrupted and homogeneous information on moderate to large earthquakes worldwide. All earthquake parameters were re-assessed using the instrumental measurements made by analysts around the world. A large proportion of the basic information for this product was sourced from paper-based historical station bulletins and more than a thousand scientific articles. All hypocenters have been re-computed with a modern location technique and velocity model. The magnitudes are represented in the same scale, the M_W . Each earthquake parameter (location, depth, magnitude) has an estimate of uncertainty and quality. The project produced reliable M_S and mb for many historical events; some of them never had such estimates made in the past. We also brought into digital existence historical station arrival picks, and body and surface wave amplitude measurements that were not digitally available in the past.

The ISC-GEM serves as a backbone for the historical part of the USGS ComCat catalog. It contributes towards the USGS seismic hazard mapping and forecasting in the US and Latin America. The catalogue helps to improve the base knowledge for calibrating the loss models used by the PAGER (Prompt Assessment of Global Earthquakes for Response) to help governmental and relief agencies. Researchers in universities and commercial companies routinely use the ISC-GEM catalogue. The catalogue also contributes towards education and capacity building in the developing world.

As a result of this project, we advanced the ISC-GEM catalogue in several areas. Information from recent scientific articles on recent and historical earthquakes was incorporated into the catalog. Another magnitude layer (M_W 5.0-5.5) of potentially damaging continental earthquakes

in the modern instrumental period was added to the catalogue. We searched the scientific literature for credible fault plane or moment tensor solutions. Additional measurements of arrival times and surface wave amplitudes have been sourced from some long-term high quality observatories and publications in an attempt to fill gaps in station reporting. Recent earthquakes for years 2015 and 2016 have been added.

Our approach was to preserve homogeneity of the ISC-GEM catalogue by applying the same techniques that have been used in production of the original version of the catalogue. The objective was to include many new earthquakes that were damaging or could have been potentially damaging and improve parameter determination of existing earthquakes. That provided more adequate representation of seismicity and associated hazard in many regions of moderate seismicity. The project resulted in the public release of substantially updated versions (Ver. 6.0 and Ver. 7.0) of the ISC-GEM catalogue.

• Report body:

Status of the catalogue before the start of the Advancement Project

The content of the ISC-GEM Catalogue for the period 1904-2014 (Version 5.0, dated 27 February 2018) is summarized in Di Giacomo et al. (2018). In Summary:

- The catalogue contained 35,225 earthquakes in total, with 7,126 listed in the Supplementary file (about 93% of them occurred before 1960);
- The pre-digital period (i.e., before 1964) is not as complete (average annual magnitude of completeness, Mc, varying between 5.7 and 6.8) as more recent decades (average annual Mc varying between 5.5 and 5.7);
- Four magnitude sources were used:
 - direct Mw from GCMT (45.7%) (www.globalcmt.org, Dziewonski et al., 1981; Ekström et al., 2012);
 - direct Mw from the literature (3.3%);
 - proxy Mw based on our recomputed MS (42.9%);
 - proxy Mw based on our recomputed mb (8.1%).
- Source mechanisms (in the form of moment tensors) were available only for earthquakes with a GCMT solution after 1976.

Objectives of the 1st Year of the Advancement Project

Objectives of the 1th Year of the ISC-GEM Advancement project were to:

- Regularize the magnitude cut-off, starting from earthquakes occurred since 1964. This task is particularly required in light of the advances following the ISC Bulletin Rebuild project (Storchak et al., 2017) and the ISC-EHB project. As detailed later, this year we focused on two time periods: 1964-1979 and 2000-2014;
- Add continental earthquakes in the magnitude range 5.0-5.5; the time periods considered this year are 1964-1979 and 2000-2015;

- Integrate source mechanisms from the literature (past and recent papers), particularly for pre-1976 earthquakes;
- Add earthquakes in 2015 based on the newly available data from the ISC Bulletin and including continental event in the magnitude range 5-5.5;
- Revise earthquakes already listed in previous versions of the ISC-GEM Catalogue by considering results discussed in the scientific literature (past and recent publications);
- Investigate apparent station report gaps, particularly for surface wave amplitude and period data during 1904-1970.

Regularizing the cut-off magnitude

For earthquakes occurred since 1964, the original selection was based on the magnitude information available at the time of the first release in 2013 (Storchak et al., 2013). Since that time, we improved the overall status of the ISC Bulletin (www.isc.ac.uk/iscbulletin/) thanks to the on going parallel project of Rebuilding the ISC Bulletin (Storchak et al., 2017). The improvements relate to both location and magnitude parameters within the ISC Bulletin thanks to the use of additional datasets and more robust review procedures. This parallel development gave us the opportunity to add earthquakes that were not selected during the first release where the magnitude information was not considered reliable (e.g., where event magnitudes based on less than 3 stations). Hence, with this task we aim to regularize the content of the catalogue toward the lower magnitude end (original cut-off magnitude of 5.5 from the 1960s onwards) by adding earthquakes that, in light of the latest results and based on the latest data available, should now be added to the ISC-GEM catalogue. By doing so we also expect to marginally improve the Mc during recent decades.

As the Rebuild project is not finished yet, we focused on two time periods that have already been accomplished: 1964-1979 and 2000-2014. The latter period also benefits from the work done by Weston et al. (2018) to create the ISC-EHB dataset, where particular attention is given to better constrain the depth of selected seismic events.

Thanks to the improved magnitude procedure introduced at the ISC (Bondár and Storchak, 2011), we searched for earthquakes in 1964-1979 and 2000-2014 not selected before with magnitude (direct or proxy Mw) > 5.45. Figure 1 summarizes the earthquakes finally added to the ISC-GEM Catalogue to regularize the cut-off magnitude during 1964-1979 and 2000-2014. The global maps in Fig.1 show how the vast majority of the earthquakes added within this task are located along major plate tectonic boundaries and mid-oceanic ridges. The timelines show a number of events significantly larger than magnitude 5.5, particularly in the period 1964-1979. We investigated in more detail those events and it occurred that such events were not selected before because they were in fact poorly recorded aftershocks of larger earthquakes. A notable exception to this is the Mw=7 shallow Fiji Islands region earthquake of 1967-01-19 (evid = 839941). This event was preceded (less than two minutes) by an intermediate-depth earthquake of magnitude 5.9 in the Santa Cruz Islands (evid = 839939) and was overlooked by many station operators. However, after consulting original sources and adding surface wave data from

printed bulletins, we were able to obtain an updated MS for evid = 839941. Our results for evid = 839941 are also supported by the finding of Isacks et al. (1969).

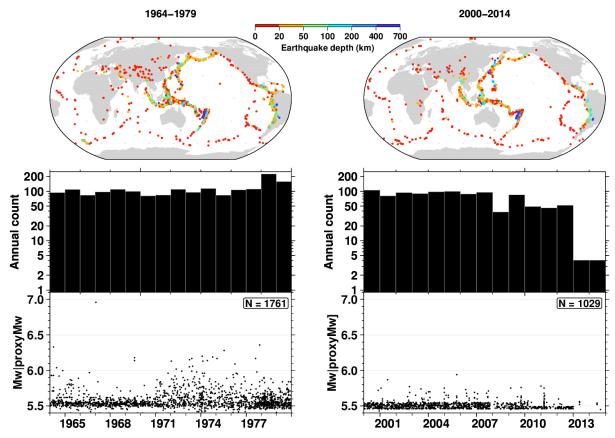


Fig. 1: Top: global distributions of the earthquakes added during 1964-1979 (left) and 2000-2014 (right) to regularize the cut-off magnitude threshold. Bottom: magnitude timelines along with their annual counts.

Continental earthquakes

Moderate shallow continental earthquakes are important for hazard studies because they can cause significant damage if occurred in populated areas. For this reason, as part of the Advancement project we add shallow earthquakes occurring within the main landmass, effectively dropping the magnitude cut-off threshold down to 5.0. It is important to note that the magnitude reliability usually deteriorates for earthquakes below magnitude 5.5, especially for those events without a direct Mw that occurred between the 1960s and 1990s (i.e., before the recent expansion of the global network of stations).

The definition of continental earthquakes is not unique. For the purposes of the ISC-GEM catalogue, we consider as continental those shallow (depth down to 60 km) earthquakes that occurred within the main continental masses of Africa, Eurasia, Americas and Australia. Hence, with this approach, we exclude events in the islands of the Pacific Ocean. Similarly to Fig.1, Fig. 2 shows the continental earthquakes added to the ISC-GEM catalogue during 1964-1979 and 2000-2014.

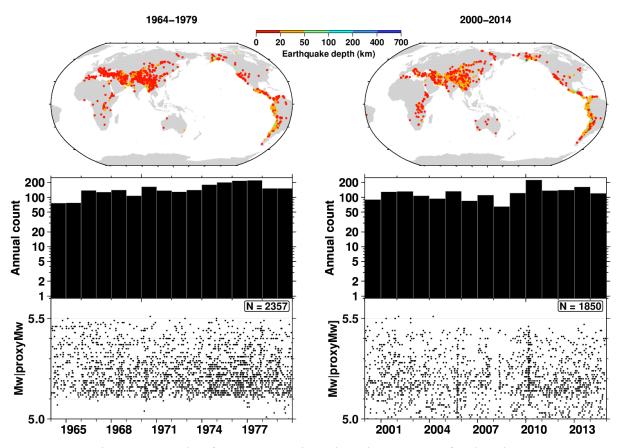


Fig. 2: Similar to Fig. 1, but for continental earthquakes; see text for details.

The global maps in Fig. 2 show how the majority of the continental earthquakes are located in Eurasia. However, a significant number of events is also added in Africa, Australia and parts of North America. The larger number of continental earthquakes in Australia during 2000-2014 compared to 1964-1979 is not due to an increase of seismic activity but to the improvements of the station network at regional and global scales that allow us to better constrain the location and magnitude of events in the southern hemisphere and in other areas of generally poor station coverage (e.g., East African rift).

As part of this task, we added significant earthquakes close to populated areas that rarely experience damaging events, such as the Dulce, New Mexico (USA) earthquake of 1966-01-23 or the Lorca (Spain) earthquake of 2011-05-11.

Source mechanisms from the literature

Following the work by Lee and Engdahl (2015), we began expanding the bibliographic search of reliable seismic moments M_0 (and, therefore, of Mw) to include source mechanisms from the literature. By source mechanism, we refer to either the six moment tensor elements and/or fault plane solutions (nodal planes described by strike, dip and rake angles). In Version 5 of the ISC-GEM catalogue there were a total of 981 direct M_0 from the literature selected from about 250 different publications. The earthquakes in the catalogue files with M_0 from the literature are identified by the value *bibliog* in the

mo_auth field. The list of earthquakes with M₀ from the literature and corresponding reference source is available at www.isc.ac.uk/iscgem/mw_bibliography.php.

The M₀ from the literature is particularly important for earthquakes before the GCMT solutions became available for global earthquakes in the late 1970s. However, due to time and resource limitations, the literature was consulted only to retrieve reliable values of M₀, even though other relevant results were available, such as source mechanisms. With the Advancement project we started to check the papers used to retrieve direct values of M₀ and add, if available and considered reliable, source mechanisms for pre-1980 earthquakes. As it will be discussed later, when checking a paper we did not limit to look for source mechanisms but we considered various aspects of the results published in a paper concerning earthquakes in the ISC-GEM catalogue. Thus, we used this opportunity also to cross-check our location results (especially depth) with the findings of authors making detailed studies for specific earthquakes or areas.

In this project year, we checked the findings from 80 research papers (out of the \sim 250 publications previously mentioned) relevant to 548 earthquakes (about 56% of the earthquakes with direct M_0 from the literature). Considering that it may be possible to obtain M_0 without a (reliable) source mechanisms, we finally accepted and added source mechanisms for 380 earthquakes, as summarized in Fig. 3.

The source mechanisms added this year are largely in the 1960s-1970s because many scientists at the time, motivated by the newly introduced theory of plate tectonics, investigated the source mechanism features in different parts of the world. Notably, the pre-1960 earthquakes (e.g., the 1905 Great Mongolian earthquakes) now also have a source mechanism.

Next year, we intend to continue checking the remaining papers and consider others (past and recent) if required. In parallel, we also explore the literature to add direct values of M_0 and, if available, source mechanisms from publications not considered by Lee and Engdahl (2015). This has been the case, for example, for a continental earthquake occurred in Australia the 1973-03-09 (evid = 762501, known as the Picton earthquake), where we added both direct M_0 and source mechanism according to Mills and Fitch (1977). To facilitate this task we benefit from the work done by the ISC to maintain the Event Bibliography (http://www.isc.ac.uk/event_bibliography/index.php, for more details see Di Giacomo et al., 2014). As a result of this on going effort, we added a direct M_0 from the literature for 28 earthquakes.

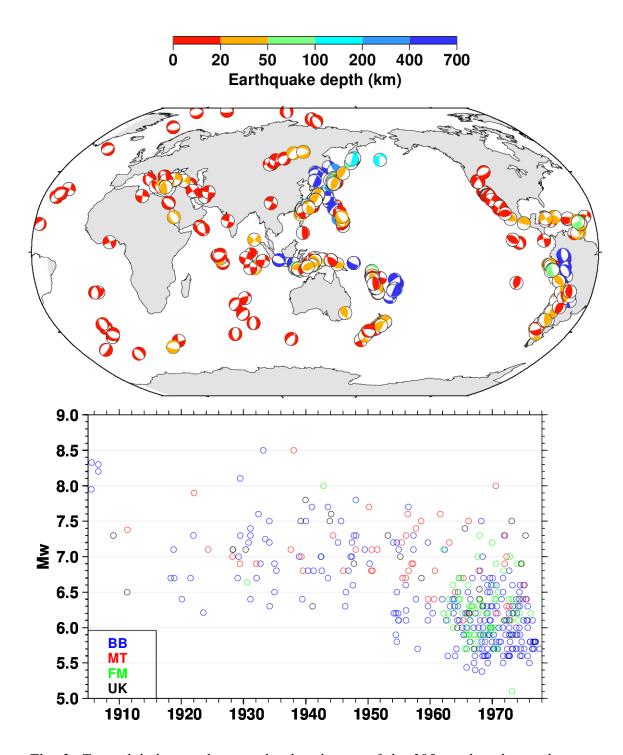


Fig. 3: Top: global map showing the distribution of the 385 earthquakes with source mechanism added from the literature. The source mechanisms are color-coded by depth. Bottom: timeline color-coded by source mechanism type: red= moment tensors (MT), blue = broadband analysis (BB); green = first motion polarities (FM); black= unknown (UK).

Earthquakes in 2015

The update of the ISC-GEM catalogue for recent years benefitted from the data collected and reviewed by ISC analysts in the course of production of the standard ISC Bulletin (www.isc.ac.uk/iscbulletin). We selected global earthquakes with magnitude 5.5 and above and added continental events (as defined earlier) with magnitude between 5.0 and 5.5. In total, we added 623 earthquakes, 143 of which occurred in continental areas. For 125 earthquakes we obtained Mw from recomputed ISC MS or mb following the same standard procedures (Di Giacomo et al., 2015b). These earthquakes with Mw proxy are often aftershocks of significant earthquakes, such as the Mw = 7.9 Gorkha (Nepal) earthquake of April 25 and the Mw = 8.2 Illapel (Chile) earthquake of September 16. The results regarding year 2015 will be included in the section describing the new version of the ISC-GEM catalogue.

Revision of earthquakes already listed in previous versions

As mentioned earlier, during the review of the literature we crosschecked our results with those available in the detailed studies from different authors. Notably, the results listed in the ISC-GEM catalogue for about 1,600 earthquakes are consistent with the literature. A small number of earthquakes already listed in previous versions required revision of location/depth and/or magnitude. The details of changes regarding such earthquakes are as follow:

- Updated location/depth for the following earthquakes:
 - evid 887959 and 887963 moved \sim 17 km SE and \sim 35 km NE, respectively, and added for both a direct M₀ from Doser (1992a);
 - evid 913126 and 911466 moved ~50 km to the East and ~130 km North-East, respectively, to better fit the results described by <u>Doser (1992b)</u>;
 - evid 910569 (1925 Santa Barbara event) moved ~90 km E, in line with the findings of Hough and Martin (2018); still accordingly to Hough and Martin (2018), we updated the magnitude from a direct Mw = 6.8 by Hanks et al. (1975) to a proxy Mw of 6.56;
 - evid 913230 moved ~145 km South in line with the results described by Stewart and Cohn (1979) and Okal et al. (2011);
 - evid 906183 moved ~68 SW and depth changed from 15 to 35 km; the new location better fits the results discussed by <u>Eissler and McNally (1984)</u> and <u>Okal and Borrero (2011)</u> Similarly, we updated evid 906234, which moved ~65 E. The new location better fits the available stations data (e.g., the secondary azimuthal gap improved from 180.4° to 95.8° and number of defining stations from 66 to 93);
 - evid 902352 has an updated depth of 60 km instead of 25 in line with the moment tensor solution of Okal and Reymond (2003);

- evid 903029 moved ~13 km SW in line with results discussed in Okal (1999);
- evid 900505 moved ~95 NE in line with the results of Doser (1990);
- evid 895348 (1950 Mondy earthquake) has depth of 15 instead of 35 km in line with the results of Delouis et al. (2002);
- evid 878424 (1960 Agadir earthquake) moved ~11 km NE and now is located on land to better fit the findings summarized by Meghraoui et al. (1998) and references therein. We also updated the Mw proxy to 5.91 based on MS from 24 stations instead of 5.84 based on MS from 3 stations;
- evid 913953 moved ~40 km N and depth changed from 15 to 10 km. The location fits better the results discussed by <u>Doser (1994)</u>;
- evid 910544 moved ~250 km NE and depth changed from 35 to 10 km.
 This change better fits the results discussed by <u>Van Dusen and Doser</u> (2000);
- depth changes following <u>Kao and Peng (1991)</u>: depth = 36.4 km instead of 20 km evid 712852 and 25 km instead of 50 km evid = 748383;
- depth change from 50 km to 40 km for evid 875869; depth change from 45 km to 35 km with epicentre moving ~30 km inland for evid 848355. Such changes are made in line with the results discussed by <u>Tichelaar and Ruff</u> (1991);
- depth change from 35 km to 60 km for evid 877305; depth change from 35 km to 53.1 km for evid 769592; depth change from 37.3 km to 60 km for evid 761389; depth change from 30 km to 15 km for evid 746346. Such changes are made in line with the results discussed by McCaffrey (1988);
- evid = 909759 has a depth of 100 km instead of 15 km and moves ~80 km to the South in line with the results of Okal and Bina (1994). The change of depth does not allow MS calculation and, therefore, evid 909759 in now listed in the Supplementary catalogue; in addition, still following Okal and Bina (1994), three earthquakes (evid 913090, 907752, 899527) in the Supplementary Catalogue that were originally shallow (at 35 or 15 km depth) are now deep or intermediate-depth events;
- evid = 902275 has an update depth of 150 km instead of 35 in line with Okal (1992);
- evid = 16958143 has an updated depth of 560 km instead of 350 km and location ~ 165 km to the North in line with the results of <u>Huang et al.</u>

- (1998). The event has also a direct Mw = 7.38 from Huang et al. (1998) and is now listed in the main catalogue;
- evid = 16958145 is an intermediate-depth event in Okal (1992) and the relocation has been updated by changing the depth from 35 km to 150 km; the epicentre also moved ~450 km NNW at the southern tip of the Kamchatka peninsula, which is closer to the original Gutenberg location. Note that the earthquake occurred in 1911 and the data available is sparse. Since the event with the location is too deep for MS calculation, it is now listed in the Supplementary catalogue;
- evid = 904192 has an update depth of 100 km instead of 15 in line with Russo et al. (1992) and Doser and Vandusen (1996). The event is still listed in the Supplementary Catalogue;
- evid = 888446 has an update depth of 100 km in line with the results of, e.g., <u>Brüstle et al. (2014)</u> and <u>Kkallas et al. (2018)</u>. The event is still listed in the Supplementary Catalogue.
- Updated magnitude for the following earthquakes:
 - evid = 852478 has a proxy Mw of 5.6 instead of a direct Mw =5.9 that was wrongly assigned to the event;
 - evid = 819518 has a direct Mw = 6.32 instead of 6.5 due to a typo in the seismic moment originally inserted from Chinn and Isacks (1983);
 - evid = 7453151 (great Sumatra earthquake of 2004-12-26) has an updated GCMT Mw = 9.3 according to <u>Tsai et al.</u> (2005) instead of the <u>standard GCMT solution</u>. M₀ has also been updated accordingly.
- Added M₀ from the literature for the following earthquakes:
 - from Okal (1992), evid = 865885 has a direct Mw = 7.16, resulting in the event being moved to the main catalogue;
 - from Okal et al. (2016), evid = 905646 has a direct Mw = 7.25;
 - from Doser (1992b), evid = 911466 has a direct Mw = 6.21.
- Additional updates are applied to the following earthquakes:
 - evid 906896 moved ~50 km SE and depth changed from 35 to 20 km;
 - depth changes from 35 km to 10 km for evid 907095, 898384, 897530, 788372, 717700, 693569; depth change from 35 to 25 km for evid 575847. All these earthquakes are off-shore the west coast of Mexico.

Station gap investigations

The search for additional stations data, with emphasis on surface wave amplitudes, is a continuous effort. During this year, this part of the project involved communications with various archives and station operators who have been asked to check their inventory and cooperate with us in data exchange and/or digitalization/scanning. As a result of this preparation work, we now plan to add the following station data:

- bulletins of Spanish stations during the 1920s-1930s;
- ➤ surface amplitude measurements from stations FRU, AAA, TAS and SEM for several years before the 1970s;
- ➤ worldwide bulletins sourced from the Obninsk (Russia) archive;

We are in contact with other archives (e.g., USGS in Menlo Park, Stuttgart) aiming to explore the possibility to add missing stations data. With such additional data we aim to improve as much as possible the quality of earthquake parameters included in the ISC-GEM catalogue.

During this project year, we have added eight earthquakes (evids 878345, 876851, 874714, 874971, 875265, 872097, 872340, 873113) between 1960 and 1963 and revised six between 1956 and 1963 (evids 885232, 882347, 877400, 875806, 872357, 872989). This has become possible thanks to the data added from individual station bulletins and additional surface wave amplitude measurements gathered from stations in former Soviet Union. We also added 17 earthquakes between 1933 and 1949, all but one from the Gutenberg and Richter catalogue; these events are undetermined shocks in the ISS and with station data not in tabulated form; to relocate and reassess the magnitude of these events we digitized and integrated parametric station data from the ISS, Gutenberg notepads, individual station bulletins and BCIS; twelve of these earthquakes (evids 16963127, 16963144, 16963678, 16964661, 16964943, 16965068, 16965286, 16965324, 16966074, 16966380, 16966502, 16967106) are listed in the *Main catalogue* and are all shallow in the magnitude range 6.0 to 6.4 (many occurring in mid-oceanic ridges); the remaining five earthquakes have poor location and/or magnitude and are listed in the *Supplementary catalogue* (evids 16963156, 16964624, 16965441, 16965882, 16965899);

Objectives of the 2nd Year of the Advancement Project

Objectives of the 2nd Year of the ISC-GEM Advancement project were to:

- Regularize the magnitude cut-off, starting from earthquakes occurred since 1964. This task is particularly required in light of the advances following the Rebuild project (Storchak et al., 2017). As detailed later, this year we focused on 1980-1990;
- Add continental earthquakes in the magnitude range 5.0-5.5; the time period considered this year is 1980-1990;
- Integrate source mechanisms from the literature (past and recent papers), particularly for pre-1976 earthquakes;

- Add earthquakes in 2016 based on the newly available data from the ISC Bulletin and including continental event in the magnitude range 5-5.5;
- Revise earthquakes already listed in previous versions of the ISC-GEM Catalogue by considering results discussed in the scientific literature (past and recent publications).

Regularizing the cut-off magnitude

For earthquakes occurred since 1964 the original selection was based on the magnitude information available at the time of the first release in 2013 (Storchak et al., 2013). Since then we improved the overall status of the ISC Bulletin (www.isc.ac.uk/iscbulletin/) thanks to the ongoing Rebuild work of the ISC Bulletin (Storchak et al., 2017). The improvements regard both location and magnitude parameters within the ISC Bulletin as the ISC was able to use additional datasets and more robust review procedures. This gives us the opportunity to add earthquakes that were not selected in the first release since the magnitude information was not considered reliable (e.g., magnitudes based on less than 3 stations). Hence, with this task we aim at regularizing the content of the catalogue toward the lower magnitude end (original cut-off magnitude of 5.5 from the 1960s onwards) by adding global earthquakes that, in light of the latest results based on the data available, should be added to the ISC-GEM Catalogue. By doing so we also expect to marginally improve the Mc over recent decades.

As the rebuild project is not finished yet, we focused on 1980-1990 for the current project year.

Thanks to the improved magnitude procedure introduced at the ISC (Bondár and Storchak. 2011), we searched for earthquakes in 1980-1990 not selected before having magnitude (direct or proxy Mw) > 5.45. Figure 4 summarizes the earthquakes finally added to the ISC-GEM Catalogue to regularize the cut-off magnitude during 1980-1990. The global maps in Fig.4 show how the vast majority of the earthquakes added within this task are located along major plate tectonic boundaries and mid-oceanic ridges.

1980-1990

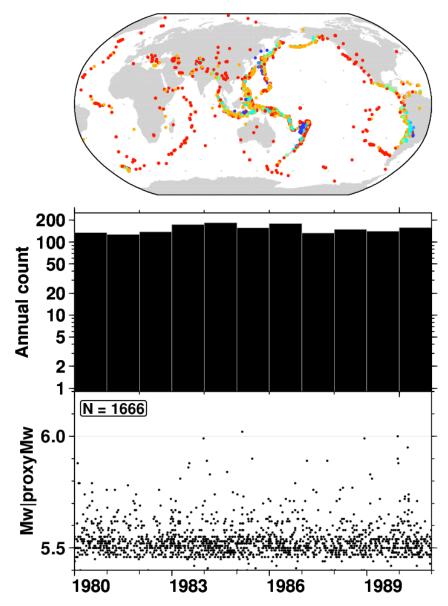


Fig. 4: Top: global distributions of the earthquakes added during 1980-1990 to regularize the cut-off magnitude threshold. Bottom: magnitude timelines along with their annual counts.

Continental earthquakes

Moderate shallow continental earthquakes are important for hazard studies as they can cause significant damage in populated areas. For this reason, in the Advancement project we add shallow earthquakes occurring in main land masses by dropping the magnitude cut-off threshold down to 5.0. It is important to remind that the magnitude reliability usually deteriorates when considering earthquakes below magnitude 5.5, especially for those events without a direct Mw that occurred between the 1960s and 1990s (i.e., before the expansion of the station global network we can process over the last ~20 years).

The definition of continental earthquakes is not uniquely defined in the seismological community. For the purposes of the ISC-GEM Catalogue, we consider as continental earthquakes shallow (depth down to 60 km) events that occurred in the main continental masses of Africa, Eurasia, Americas and Australia. Hence, with this approach, we exclude events occurring in the islands of the Pacific Ocean. Similarly to Fig.4, Fig. 5 shows the continental earthquakes finally added to the ISC-GEM Catalogue during 1980-1990.

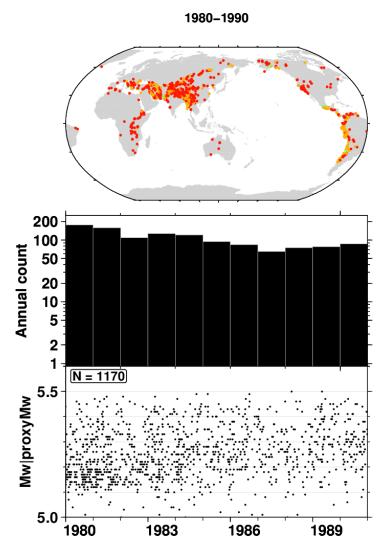


Fig. 5: As for Fig. 1 but for continental earthquakes. See text for details.

The global maps of Fig. 5 highlight how most of the continental earthquakes are located in Eurasia. However, a significant number of events is also added in Africa and parts of North America.

Earthquakes in 2016

The update of the ISC-GEM Catalogue for recent years benefits from the data collected and reviewed by ISC analysts to produce the ISC Bulletin (www.isc.ac.uk/iscbulletin). We selected global earthquakes with magnitude 5.5 and above and, in addition, added continental events (as defined earlier) with magnitude between 5.0 and 5.5. In total, we added 595 earthquakes in 2016, 98 of which are from continental areas. For 62 earthquakes we obtained Mw from our recomputed mb following the same procedures adopted in previous version of the ISC-GEM Catalogue (Di Giacomo et al., 2015b). These earthquakes with Mw proxy are often aftershocks of significant earthquakes.

Direct M_0 and source mechanisms from the literature

Following the work by Lee and Engdahl (2015), we started to expand the bibliographic search of reliable seismic moments M_0 (and, therefore, of Mw) to include also source mechanisms from the literature. With source mechanism here we refer either to the six moment tensor elements and/or fault plane solutions (nodal planes described by strike, dip and rake angles). In Version 5 of the ISC-GEM catalogue we included a total of 981 direct M_0 from the literature selected from about 250 different publications. The earthquakes in the catalogue files having M_0 from the literature are identified by the value bibliog in the mo_auth field. The list of earthquakes with M_0 from the literature and corresponding reference source is available at www.isc.ac.uk/iscgem/mw bibliography.php.

The M₀ from the literature is particularly important for earthquakes before the GCMT solutions became available for global earthquakes in the late 1970s. However, due to time and resource limitations, the literature was consulted only to retrieve reliable values of M₀, even though other relevant results were available, such as source mechanisms. With the Advancement project we started to check the papers used to retrieve direct values of M₀ and add, if available and considered reliable, source mechanisms for earthquakes without a GCMT solution. As it will be discussed later, when checking a paper, we did not limit to look for source mechanisms, but we considered various aspects of the results published in a paper concerning earthquakes in the ISC-GEM catalogue. Thus, we used this opportunity also to cross-check our location results (especially depth) with the findings of authors making detailed studies for specific earthquakes or areas. During this task we did not limit to check only the papers considered by Lee and Engdahl (2015) but expanded the literature search to other publications (past and recent) to include new values of direct M₀ for earthquakes which were listed in the catalogue with a proxy Mw. This task applies both to earthquakes already listed in Version 5 of the ISC-GEM Catalogue and to earthquakes added during the Advancement project.

In this project year, we checked the results in 160 papers which consider 323 earthquakes in total and added for the first time direct M_0 values from the literature for 74 earthquakes (details for individual earthquakes to be outlined in the next section). Considering that it may be possible to obtain M_0 without a (reliable) source mechanisms, we finally accepted and added source mechanisms for ~273, as summarized in Fig. 6.

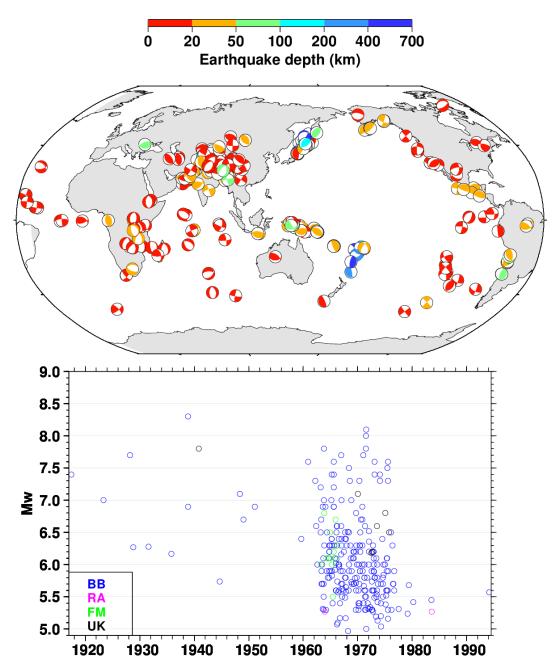


Fig. 6: Top: global map showing the distribution of the 273 earthquakes with source mechanism added from the literature. The source mechanisms are color-coded by depth. Bottom: timeline color-coded by source mechanism type: blue = broadband analysis (BB); magenta= relative amplitudes; green = first motion polarities (FM); black= unknown (UK).

The source mechanisms added this year are largely in the 1960s-1970s as many authors, motivated by the newly introduced theory of plate tectonics, investigated the source mechanism features in different parts of the world.

In the next year project we intend to continue to check the remaining papers and consider others (past and recent). In parallel, we also explore the literature to add direct values of

M₀ and, if available, source mechanisms from publications not considered by Lee and Engdahl (2015). To facilitate this task we benefit from the work done by the ISC to maintain the Event Bibliography (http://www.isc.ac.uk/event_bibliography/index.php, for more details see Di Giacomo et al., 2014).

Revision of earthquakes already listed in previous versions

As mentioned earlier, during the review of the literature we cross-checked our results with those available in the detailed studies from different authors. A limited number of earthquakes already listed in previous versions required revision of location/depth and/or magnitude. The details of changes regarding such earthquakes are as follow:

- Updated location/depth/magnitude for the following earthquakes:
 - from Martin et al. (2019), evid = 16957943 (1907-01-04 off coast Sumatra earthquake) has an updated direct Mw = 8.2 instead of a direct Mw = 7.8 from Kanamori et al. (2010). Event location also updated about 150 km Eastward (from lat = 2.42, lon = 94.26, depth = 15 km to lat = 2.68, lon = 95.53, depth = 25 km). The revised location is in line with the results of Martin et al. (2019) and their interpretation of this large earthquake;
 - from Anderson et al. (1989), added direct Mw for eight major earthquakes (evid 16957987, 16957988, 16958175, 913745, 908552, 908823, 908920, 905294) near the coast of Guerrero, Oaxaca and Jalisco (Mexico). The magnitude changes are in range ±0.3 units. As a result, evid = 16957988 now is listed in the Main catalogue. In addition, for evid 16957987 and 16957988 the location has been revised 170 and 300 km to the South, respectively, and depth from 80 and 70 km, respectively, to 25 km;
 - Evid = 16958007 (1908-12-12 Myanmar earthquake) has an updated location (about 29 km NNE) after adding arrival times from station ZKW and following a revision of the event after Di Giacomo and Dewey (2019);
 - Evid = 912683 has been relocated 350 km South-west and depth (fixed) also updated from 15 km to 25 km. We thank **Víctor García** for pointing out the mis-location of this event;
 - Evid 908489 and 908604 have an updated fixed depth of 80 km in place of depths of 15 km and 35 km, respectively. The locations moved about 35 and 87 km to the West for evid 908489 and 908604, respectively. Depth and location changes have been done taking into account the results of Jimenez and Ponce (1978);
 - from <u>Iosif et al (1979)</u>, four intermediate-depth earthquakes (evid 908373, 904861, 901664, 899085) in the Vrancea region have direct Mw. As a result, these four events are now listed in the Main catalogue;
 - from Bent (1996), evid = 904623 has a direct Mw = 6.17 ± 0.2 instead of proxy Mw = 6.27 ± 0.2 and source mechanism added;
 - from Bent and Helmberger (1991), three earthquakes in Southern California have direct Mw: evid 903010 and 900505 have Mw = 6.0 and 6.28 in place of proxy Mw = 6.1 and 6.5, respectively, whereas evid = 900506, previously in the Supplementary catalogue, is now listed in the Main catalogue with Mw =6.05 and an updated location about 80 km to

- the North;
- evid = 901696 (1940-11-10 Vrancea earthquake) has an updated depth of 150 km instead of 90 km and location ~11 km to the West. The direct Mw = 7.8±0.4 from <u>Iosif et al. (1979)</u> has been updated with a direct Mw = 7.74±0.3 from <u>Oncescu and Bonjer (1997)</u> and source mechanism added. The depth update is in line with the interpretation of the event by Oncescu and Bonjer (1997);
- <u>from Bent (1996)</u>, evid = 899531, previously in the Supplementary catalogue, has a direct Mw = 5.74±0.3 and source mechanism added;
- Evid = 895445 (1950-05-21 Cusco earthquake) has been relocated with a depth of 10 instead of 100 km. The location moved ~12 km East. Not enough surface wave amplitude data is available to re-compute MS, therefore the event remains listed in the Supplementary Catalogue. We thank Léo Marconato for pointing out the shallow nature of this event;
- from Muller (1983), evid = 864118 has a direct Mw = 6.1 ± 0.3 in place of proxy Mw = 5.57 ± 0.4 , and source mechanism added;
- from Hanks (1971), evid = 875343 has a direct Mw = 5.93 ± 0.3 in place of proxy Mw = 6.16 ± 0.35 ;
- from Raeesi and Atakan (2009), evid = 871982 has an updated direct Mw
 = 7.65 instead of a direct Mw = 7.2 from Hanks (1971), and source mechanism added;
- from <u>Huang and Solomon (1987)</u>, evid 861576 and 844503 have an updated direct Mw = 5.8±0.2 and 5.70±0.2, respectively, instead of direct Mw = 6.3 and 6.0, respectively, from <u>Tsai (1969)</u>. Source mechanism added for these two events;
- from <u>Kao and Chen (1994)</u>, evid 857484 and 766673 have direct Mw = 5.83 and 5.89, respectively, instead of proxy Mw = 5.7 and 5.65, respectively, and source mechanisms added as well;
- from Forsyth (1973), evid 852214 has a direct $Mw = 5.92\pm0.3$ in place of proxy $Mw = 6.21\pm0.31$, and source mechanism added;
- from Quittmeyer et al. (1984), evid 851175, 849961, 849991, 844039, 765097 have direct Mw in place of proxy Mw values as well as source mechanisms added. The largest magnitude change, from 6.45 to 6.09, occurs for evid = 849991. In addition, for evid = 849961 the direct Mw = 6.5 ±0.4 from Brune and Engen (1969) has been updated with a direct Mw = 6.28±0.3, and source mechanism added;
- · from Shudofsky (1985), evid 849441, 847524, 842196, 778530, 776171, 749720, 731621, 695596 have direct Mw in place of proxy Mw values as well as source mechanisms added. The largest magnitude change, from 5.53 to 5.07, occurs for evid = 849441;
- from Bergman et al. (1984), evid 851845 and 665450 have direct Mw = 6.0 and 5.7, respectively, instead of proxy Mw = 5.6 and 5.7, respectively, and source mechanisms added as well;
- from Quittmeyer and Kafka (1984), evid 849714, 770300, 770384, 736097 have direct Mw in place of proxy Mw values as well as source mechanisms added. The largest magnitude change, from 5.68 to 5.3,

- occurs for evid = 770300:
- from Bergman and Solomon (1984), evid = 849961 has an updated direct Mw = 6.6±0.3 instead of a direct Mw = 6.42±0.2 from Forsyth (1973), and evid = 766025 has a direct Mw = 5.54 instead of proxy Mw = 5.59. Source mechanism added for these two events;
- from Zhou et al. (1983), evid = 832769 has a direct Mw = 5.5 in place of proxy Mw = 5.83 as well as source mechanisms added;
- from Chen and Forsyth (1978), evid = 829308 has an updated direct Mw = 6.3 instead of a direct Mw = 6.4 from Molnar and Wyss (1972), and evid = 769977 has a direct Mw = 6.2 in place of a proxy Mw = 6.2. Source mechanism added for both earthquakes;
- from Chung (1993), evid = 798304 has a direct Mw = 5.36 in place of proxy Mw = 5.45 as well as source mechanisms added;
- from <u>Priestley et al. (1994)</u>, evid = 794114 has an updated direct Mw = 6.36 instead of a direct Mw = 6.7 from <u>North (1977)</u>. Evid 787393 has an updated direct Mw = 5.67 instead of a proxy Mw = 5.85. Source mechanism added for both earthquakes;
- from Abers and McCaffrey (1994), evid 777013 and 777043 have direct Mw (6.52 and 6.36, respectively) in place of proxy Mw (6.63 and 6.57, respectively) values as well as source mechanisms added;
- from Abers and McCaffrey (1988), evid = 766904 has a direct Mw = 5.27 in place of proxy Mw = 5.79 as well as source mechanisms added;
- from Nelson et al. (1987), evid = 774259 has a direct Mw = 5.34 in place of proxy Mw = 5.73 as well as source mechanisms added. Depth updated for evid 852398 and 598460 to 45 and 20 km, respectively, instead of 35 and 30.9, respectively:
- from Chen and Molnar (1983), evid 757320 and 726312 have direct Mw (5.42 and 5.16, respectively) in place of proxy Mw (5.78 and 5.37, respectively) values as well as source mechanisms added;
- from Zheng and Suzuki (1993), evid = 772832 (1972-06-24 Hindu-Kush region earthquake) has a direct Mw = 6.18 in place of a proxy Mw = 6.31 as well as source mechanism added;
- from Singh and Wyss (1976), evid = 757676 (1973-08-28 Puebla earthquake) has a direct Mw = 7.05 and it is now listed in the main catalogue;
- Evid = 745522 and 824904 have an updated direct Mw = 6.55 and 6.51, respectively, instead of 6.4 after correcting typos in the seismic moment originally inserted from Huang and Chen (1986) and Chung and Kanamori (1980);
- from Estabrook et al. (1992), evid = 647474 has a direct Mw = 5.24 in place of a proxy Mw = 5.52 as well as source mechanism added;
- from Xu and Chen (1997), evid = 185689 has a direct Mw = 5.57 in place of a proxy Mw = 5.84 as well as source mechanism added;
- We thank **Max Suter** for pointing out papers with direct estimations of M₀ (hence of Mw) for the following events:

- from <u>Doser and Rodriguez (1987)</u>, evid = 908949 (1928-11-01 Parral earthquake) has a direct Mw = 6.27 in place of a proxy Mw = 6.47 and source mechanism added;
- from Doser (1987), evid = 906944 (1934-08-16 Valentine earthquake) has a direct Mw = 6.28 in place of a proxy Mw = 6.51 as well as a source mechanism;
- from Suárez (2000), evid 882734 and 837720 have direct Mw = 6.4 and 5.62 in place of proxy Mw =6.36 and 5.86, respectively, and source mechanisms added.
- Events added following the review of the bibliographic search by <u>Lee and</u> Engdahl (2015):
 - from Assumpção and Suárez (1988), added evid = 873757 (1963-12-14 Brazil earthquake) with direct Mw = 5.27. Source mechanisms added as well:
 - from Bergman and Solomon (1984), added three earthquakes (evid 829246, 829275, 797139) in the Chagos Archipelago region with direct Mw in the range 5.4-5.65. Source mechanisms added as well;
 - from Quittmeyer and Kafka (1984), added five earthquakes (evid 872915, 823471, 814962, 756024, 760813) in Southern / off coast Pakistan with direct Mw in the range 5.0-5.7. Source mechanisms added as well;
 - from Forsyth (1973), added three earthquakes (evid 841093, 808352, 804292) in the East Pacific Rise / Galapagos with direct Mw in the range 5.7-6.2. Source mechanisms added as well;
 - from Shudofsky (1985), added evid = 830319 (1967-10-14 Kenya earthquake) with direct seismic moment (Mw = 5.17) as well as its source mechanism;
 - · from <u>Grimison and Chen (1988)</u>, added evid = 732326 (1975-02-15 Mozambique Channel earthquake) with direct seismic moment (Mw = 5.38) as well as its source mechanism;
 - from Petroy and Wiens (1989), added evid = 649381 (1980-03-11 South Indian Ocean earthquake) with direct seismic moment (Mw = 5.42) as well as its source mechanism;
- Updates following the review done in the Rebuild project (Storchak et al., 2017):
 - updated the magnitude for three earthquakes (evid 395561, 395562, 395579) of the 1989 Afar sequence. The proxy Mw values are now based on mb instead of MS and in the range 5.3-5.5 instead of 6.1-6.6;
 - evid = 376632 has an updated proxy Mw = 6.02 ± 0.66 based on mb instead of a proxy Mw= 7.13 ± 0.34 based on MS;
 - · For close events 234119 and 234120 we have re-associated the GCMT solution from 234119 to 234120; evid = 234119 is now listed in the Supplementary Catalogue as its proxy Mw based on mb has high uncertainty;
 - evid = 228648 has an updated proxy Mw = 5.8 ± 0.58 based on mb instead

- of a proxy Mw= 6.60 ± 0.26 based on MS;
- Deleted three earthquakes (430746, 396787, 505928) from the Main and one from the Supplementary catalogue (evid = 167106); these are events close in time to larger earthquakes with magnitude originally overestimated;
- evid = 1742706 has an updated proxy Mw = 5.5 ± 0.34 based on mb instead of a proxy Mw= 6.1 ± 0.2 based on MS;757676
- evid = 1841012 has an updated proxy Mw = 6.2 ± 0.62 based on mb instead of a proxy Mw= 6.71 ± 0.43 based on MS;
- evid = 7143736 has an updated proxy Mw = 5.3 ± 0.3 based on mb instead of a proxy Mw= 5.8 ± 0.4 based on MS;
- evid = 11122103 has an updated proxy Mw = 5.32±0.26 based on mb instead of a proxy Mw= 6.23±0.25 based on MS;

Station gap investigation

The search for additional stations data, with emphasis on surface wave amplitudes, is a continuous ISC effort. Most of this year activity to investigate station gaps involved communications with various archives and station operators to check their inventory and cooperate with us to facilitate the data exchange and/or digitalization. This year we have added about 2300 reading from printed station bulletins from 40 stations globally distributed between 1920 and 1950. The data added is associated to over 1,000 earthquakes and will be processed in the two years of the Advancement project. We are particularly grateful to Rudolf Widmer-Schnidrig from the Black Forest Observatory (Germany) for allowing us to ship to the ISC many boxes with printed bulletins from the archive of the University of Stuttgart.

Other archives (e.g., USGS in Menlo Park, Stuttgart) are in contact with us to explore the possibility to add stations data. With such additional station data, we aim at improving as much as possible the quality of the earthquake included in the ISC-GEM Catalogue.

Summary for Year 1 and Year 2

During the 1st and 2nd years of the ISC-GEM Advancement project we:

- relocated ~10,500 earthquakes that occurred between 1964-1990 and 2000-2014;
- added 1,218 earthquakes that occurred in 2015-2016 period;
- sourced from the literature 648 source mechanisms for pre-GCMT earthquakes and expanded the format of the catalogue files to list also the nodal planes (if any) beside the moment tensor elements;
- added seven earthquakes between 1956 and 1963 and revised the solutions of approximately 140 earthquakes, mostly in the 1960s and 1970s, already listed in previous versions;
- publicly released Ver 6.0 and Ver. 7.0 of the ISC-GEM catalogue; Figure 7 shows the daily statistics of the ISC-GEM downloads by professionals in the field; on average, throughout 2019-2020, a copy of the catalog is downloaded through the sign-up

procedure every 80 minutes, with peaks observed during the new version releases, when registered users respond to notifications from the ISC.

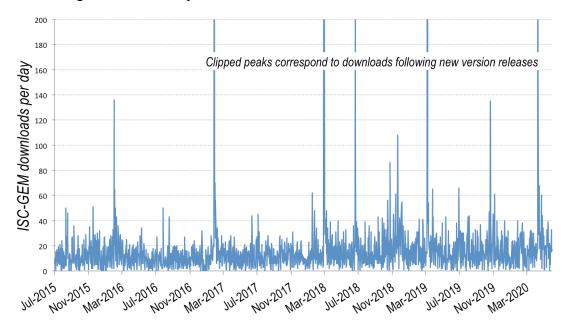


Figure 7. Daily statistics of the ISC-GEM catalog downloads; large peaks are not to scale (330 downloads on Jan 27, 2017; a total of 476 on Feb 27-28, 2018; a total of 326 on June 20-21, 2018; a total of 466 on Mar 7-8, 2019 and a total of 469 on April 9-10, 2020) correspond to days when notifications on major version releases are communicated to regular users who registered themselves in the ISC-GEM catalog sign-up list. Courtesy of Google Analytics.

The updated plot of the time-magnitude distribution of the ISC-GEM main catalogue 1904-2016 is shown in Figure 8 (for comparison with previous version see Figure 25 of Di Giacomo et al., 2018).

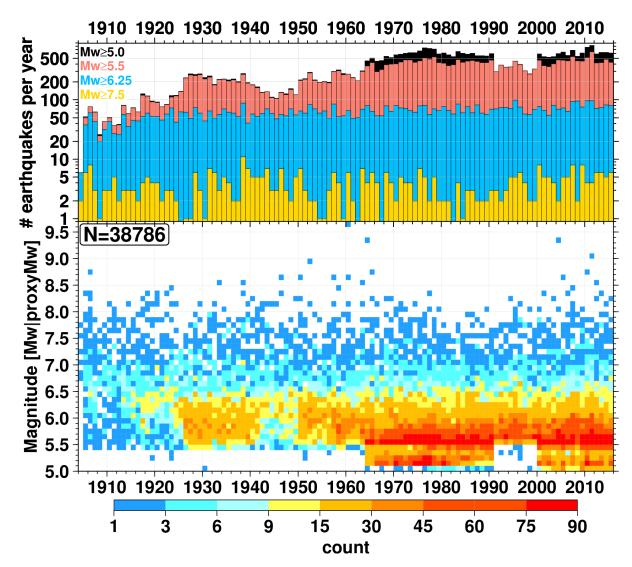


Fig. 8: Top: cumulative annual number of earthquakes with $Mw \ge 5.0$ (black), $Mw \ge 5.5$ (red), ≥ 6.5 (blue) and ≥ 7.5 (yellow); Bottom: time-magnitude distribution color-coded in cells of 0.1 Mw units for each year of the ISC-GEM Catalogue.

References

Abers, G. and McCaffrey, R. (1988). Active deformation in the New Guinea fold-and-thrust belt: Seismological evidence for strike-slip faulting and basement-involved thrusting, J. geophys. Res., 93, B11, 13332-13354, http://doi.org/10.1029/JB093iB11p13332.

Abers, G.A. and McCaffrey, R. (1994). Active arc-continent collision: earthquakes, gravity anomalies, and fault kinematics in the Huon-Finisterre collision zone, Papua New Guinea, Tectonics, 13, 2, 227-245, http://doi.org/10.1029/93TC02940.

Anderson, A.G., Singh, S.K., Espindola, J.M. and Yamamoto, J. (1989). Seismic strain

release in the Mexican subduction thrust, Phys. Earth planet. Interiors, 58, 4, 307-322, http://doi.org/10.1016/0031-9201(89)90102-7

Assumpção, M. and Suárez, G. (1988). Source mechanisms of moderate-size earthquakes and stress orientation in mid-plate South America, Geophys. J. Int., 92, 2, 253-267, http://doi.org/10.1111/j.1365-246X.1988.tb01138.x.

Bent, A.L. and Helmberger, D.V. (1991). A re-examination of historic earthquakes in the San Jacinto fault zone, California, Bull. seism. Soc. Am. 81, 6, 2289-2309.

Bent, A.L. (1996). Source parameters of the damaging Cornwall-Massena earthquake of 1944 from regional waveforms, Bull. seism. Soc. Am. 86, 2, 489-497.

Bent, A.L. (1996). Am improved source mechanism for the 1935 Timiskaming, Quebec earthquake from regional waveforms, Pure appl. Geophys., 146, 1, 5-20, http://doi.org/10.1007/BF00876667.

Bergman, E.A. and Solomon, S.C. (1984). Source mechanisms of earthquakes near midocean ridges from body-waveform inversion: Implications for the early evolution of oceanic lithosphere, J. geophys. Res., 89, B13, 11415-11441, http://doi.org/10.1029/JB089iB13p11415.

Bergman, E.A., Nábělek, J.L. and Solomon, S.C. (1984). An extensive region of off-ridge normal-faulting earthquakes in the southern Indian Ocean, J. geophys. Res., 89, B4, 2425-2443, http://doi.org/10.1029/JB089iB04p02425.

Bondár, I. and D. Storchak, 2011. Improved location procedures at the International Seismological Centre, Geophys. J. Int., 186, 1220-1244, doi: 10.1111/j.1365-246X.2011.05107.x.

Bondár, I., E.R. Engdahl, A. Villaseñor, J. Harris and D.A. Storchak, 2015. ISC-GEM: Global Instrumental Earthquake Catalogue (1900-2009): II. Location and seismicity patterns, Phys. Earth Planet. Int., 239, 2-13, doi: 10.1016/j.pepi.2014.06.002.

Brüstle, A., Friederich, W., Meier, T. and Gross, C. (2014). Focal mechanism and depth of the 1956 Amorgos twin earthquakes from waveform matching of analogue seismograms, Solid Earth, 5, 1027-1044, doi: 10.5194/se-5-1027-2014.

Chen, T. and Forsyth, D.W. (1978). A detailed study of two earthquakes seaward of the Tonga Trench: Implications for mechanical behavior of the oceanic lithosphere, J. geophys. Res., 83, B10, 4995-5003, http://doi.org/10.1029/jb083ib10p04995.

Chen, W.-P. and Molnar, P. (1983). Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, J. geophys. Res., 88, B5, 4183-4214, http://doi.org/10.1029/JB088iB05p04183.

Chinn, D. and Isacks, B. (1983). Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides Island Arc, Tectonics, 2, 529-563, doi: 10.1029/TC002i006p00529.

- Chung, W.Y. (1993). Source parameters of two rift associated intraplate earthquakes in peninsular India: the Bhadrachalam earthquake of April 13, 1969 abd the Broach earthquake of March 23, 1970, Tectonophysics, 225, 219-230, http://doi.org/10.1016/0040-1951(93)90281-N.
- Chung, W.Y. and Kanamori, H. (1980). Variations of source parameters and stress drops within a descending slab and its implications in plate mechanics, Phys. Earth planet. Interiors, 23, 134-159, http://doi.org/10.1016/0031-9201(80)90008-4.
- Delouis, B., Déverchère, J., Melnikova, V., Radziminovitch, N., Loncke, L., Larroque, C., Ritz, J.F. and San'kov, V. (2002). A reappraisal of the 1950 (Mw 6.9) Mondy earthquake, Siberia, and its relationship to the strain pattern at the south-western end of the Baikal rift zone, Terra Nova, 14, 6, 491-500, doi: 10.1046/j.1365-3121.2002.00445.x.
- Di Giacomo, D., Storchak, D.A., Safronova, N., Ozgo, P., Harris, J., Verney, R. and Bondár, I., 2014. A New ISC Service: The Bibliography of Seismic Events, Seismol. Res. Lett., 85, 2, 354-360, doi: 10.1785/0220130143
- Di Giacomo, D., Harris, J., Villaseñor, A., Storchak, D.A., Engdahl, E.R., Lee, W.H.K. and the Data Entry Team, 2015a. ISC-GEM: Global Instrumental Earthquake Catalogue (1900-2009), I. Data collection from early instrumental seismological bulletins, Phys. Earth Planet. Inter., 239, 14-24, doi: 10.1016/j.pepi.2014.06.003.
- Di Giacomo, D., I. Bondár, D.A. Storchak, E.R. Engdahl, P. Bormann and J. Harris, 2015b. ISC-GEM: Global Instrumental Earthquake Catalogue (1900-2009): III. Recomputed MS and mb, proxy MW, final magnitude composition and completeness assessment, Phys. Earth Planet. Int., 239, 33-47, doi: 10.1016/j.pepi.2014.06.005.
- Di Giacomo, D., Engdahl, E. R. and Storchak, D.A. (2018). The ISC-GEM Earthquake Catalogue (1904–2014): status after the Extension Project, Earth Syst. Sci. Data, 10, 1877-1899, doi: 10.5194/essd-10-1877-2018.
- Di Giacomo, D. and Dewey, J.W. (2020). The (Mythical) M 8.2 Off Coast of Peru Earthquake of 12 December 1908, Seismol. Res. Lett., http://doi.org/10.1785/0220190232
- Doser, D.I. (1990). Source characteristics of earthquakes along the southern San Jacinto and Imperial fault zones (1937 to 1954), Bull. seism. Soc. Am. 80, 5, 1099-1117.
- Doser, D.I. (1992a). Faulting processes of the 1956 San Miguel, Baja California, earthquake sequence, Pure appl. Geophys., 139, 1, 3-16, http://doi.org/10.1007/BF00876824
- Doser, D.I. (1992b). Historic earthquakes (1918 to 1923) and an assessment of source parameters along the San Jacinto fault system, Bull. seism. Soc. Am. 82, 4, 1786-1801.
- Doser, D.I. (1994). Contrasts between source parameters of $M \ge 5.5$ earthquakes in northern Baja California and southern California, Geophys. J. Int., 116, 3, 605-617, doi: 10.1111/j.1365-246X.1994.tb03284.x.
- Doser, D.I. and Vandusen, S.R. (1996). Source processes of large (M≥6.5) earthquakes of

the Southeastern Caribbean (1926–1960), Pure appl. Geophys., 146, 1, 43-66, doi: 10.1007/BF00876669.

Dziewonski, A.M., Chou, T.-A. and Woodhouse, J.H. (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, J. geophys. Res., 86, B4, 2825-2852, doi: 10.1029/JB086iB04p02825.

Eissler, H.K. and McNally, K.C. (1984). Seismicity and tectonics of the Rivera Plate and implications for the 1932 Jalisco, Mexico, earthquake, J. geophys. Res., 89, B6, 4520-4530, doi:10.1029/JB089iB06p04520.

Estabrook, C.H., Nábělek, J.L. and Lerner-Lam, A.L. (1992). Tectonic model of the Pacific-North American plate boundary in the Gulf of Alaska from broadband analysis of the 1979 St. Elias, Alaska, earthquake and its aftershocks, J. geophys. Res., B, 97, 5, 6587-6612, http://doi.org/10.1029/92JB00131.

Ekström, G., Nettles, M. and Dziewonski, A.M. (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes, Phys. Earth planet. Interiors, 200–201, 1-9, doi: 10.1016/j.pepi.2012.04.002.

Forsyth, D.W. (1973). Anisotropy and the structural evolution of the oceanic upper mantle, Ph.D. Thesis, MIT, Cambridge.

Grimison, N.L. and Chen, W-P. (1988). Earthquakes in the Davie Ridge-Madagascar region and the southern Nubian-Somalian plate boundary, J. geophys. Res., B, 93, 9, 10439-10450, http://doi.org/10.1029/JB093iB09p10439.

Hanks, T.C., Hileman, J.A. and Thatcher, W. (1975). Seismic moments of the larger earthquakes of southern California region, Geol. Soc. Am. Bull., 86, 1131-1139, doi: 10.1130/0016-7606(1975)86<1131:SMOTLE>2.0.CO;2.

Hough, S.E. and Martin, S.S. (2018), A proposed rupture scenario for the 1925 MW 6.5 Santa Barbara, California, earthquake, Tectonophysics, 747-748, 211-224, doi: 10.1016/j.tecto.2018.09.012/

Huang, W.C., Okal, E.A., Ekström, G. and Salganik, M.P. (1998). Centroid moment tensor solutions for deep earthquakes predating the digital era: The historical dataset (1907-1961), Phys. Earth planet. Interiors, 106, 181-190, http://doi.org/10.1016/S0031-9201(98)00081-8.

Huang, J. and Chen, W.-P. (1986). Source mechanisms of the Mogod earthquake sequence of 1967 and the event of 1974 July 4 in Mongolia, Geophys. J. R. astr. Soc., 84, 2, 361-379, http://doi.org/10.1111/j.1365-246X.1986.tb04360.x.

Huang, P.Y. and Solomon, S.C. (1987). Centroid depths and mechanisms of mid-ocean ridge earthquakes in the Indian Ocean, Gulf of Aden, and Red Sea, J. geophys. Res., 92, B2, 1361-1382, http://doi.org/10.1029/JB092iB02p01361.

Iosif, S., Prochazkova, D. and Iosif, T. (1979). Seismic source parameters of large earthquakes in Vrancea, Tectonophysics, 53, 3-4, 195-201, http://doi.org/10.1016/0040-1951(79)90064-7.

Isacks, B., Sykes, L.R. and Oliver, J. (1969). Focal mechanisms of deep and shallow earthquakes in the Tonga-Kermadec region and the tectonics of Island Arcs, GSA Bulletin, 80, 8, 1443, DOI: 10.1130/0016-7606(1969)80[1443:FMODAS]2.0.CO;2.

Jimenez, Z. and Ponce, L. (1978). Focal mechanism of six large earthquakes in northern Oaxaca, Mexico, for the period 1928-1973, Geofis. int. 17, 3, 379-386.

Kao, H. and Chen, W.-P. (1994). The double seismic zone in Kuril-Kamchatka: The tale of two overlapping single zones, J. geophys. Res., 99, B4, 6913-6930, http://doi.org/10.1029/93JB03409.

Kanamori, H., Rivera, L. and Lee, W.H.K. (2010). Historical seismograms for unravelling a mysterious earthquake: The 1907 Sumatra Earthquake, Geophys. J. Int., 183, 1, 358-374, http://doi.org/10.1111/j.1365-246X.2010.04731.x

Kao, H. and Chen, W.-P. (1991). Earthquakes along the Ryukyu-Kyushu Arc: Strain segmentation, lateral compression, and the thermomechanical state of the plate interface, J. geophys. Res., 96, B13, 21443-21485, doi: 10.1029/91JB02164.

Kkallas, C., Papazachos, C.B., Boore, D., Ventouzi, C. and Margaris, B.N. (2018). Historical intermediate-depth earthquakes in the southern Aegean Sea Benioff zone: modeling their anomalous macroseismic patterns with stochastic ground-motion simulations, Bull. Earthquake Eng., 16, 11, 5121-5150, doi: 10.1007/s10518-018-0342-8.

Lee, W.H.K. and E.R. Engdahl, 2015. Bibliographical search for reliable seismic moments of large earthquakes during 1900-1979 to compute MW in the ISC-GEM Global Instrumental Reference Earthquake Catalogue (1900-2009), Phys. Earth Planet. Int., 239, 25-32, doi: 10.1016/j.pepi.2014.06.004.

Martin, S.S., Li, L., Okal, E.A., Morin, J., Tetteroo, A.E.G., Switzer, A.D. and Sieh, K.E. (2019). Reassessment of the 1907 Sumatra "Tsunami Earthquake" Based on Macroseismic, Seismological, and Tsunami Observations, and Modeling, Pure appl. Geophys., 176, 7, 2831-2868, http://doi.org/10.1007/s00024-019-02134-2

McCaffrey, R. (1988). Active tectonics of the eastern Sunda and Banda arcs, J. geophys. Res., 93, B12, 15163-15182, doi: 10.1029/JB093iB12p15163.

Meghraoui, M., Outtani, F., Choukri, A., & De Lamotte, D. F. (1999). Coastal Tectonics across the South Atlas Thrust Front and the Agadir Active Zone, Morocco. Geological Society, London, Special Publications, 146(1), 239–253. doi:10.1144/gsl.sp.1999.146.01.14.

Mills, J.M. and Fitch, T.J. (1977). Thrust faulting and crust-upper mantle structure in East Australia, Geophys. J. R. astr. Soc., 48, 3, 351-384, doi: 10.1111/j.1365-246X.1977.tb03677.x

Muller, J.L. (1983). Earthquake source parameters, seismicity, and tectonics of North Atlantic transform faults, Ph.D. Thesis, MIT, Cambridge.

Nelson, M.R., McCaffrey, R. and Molnar, P. (1987). Source parameters for 11

earthquakes in the Tien Shan, Central Asia, determined by P and SH waveform inversion, J. geophys. Res., 92, B12, 12629-12648, http://doi.org/10.1029/JB092iB12p12629.

Okal, E.A. (1992). Use of the mantle magnitude Mm for the reassessment of the moment of historical earthquakes. II: intermediate and deep events, Pure appl. Geophys., 139, 1, 59-85, doi: 10.1007/BF00876826.

Okal, E.A. (1999). Historical seismicity and seismotectonic context of the great 1979 Yapen and 1996 Biak, Irian Jaya earthquakes, Pure appl. Geophys., 154, 3-4, 633-675, doi: 10.1007/s000240050247.

Okal, E.A. and Bina, C.R. (1994). The deep earthquakes of 1921-1922 in northern Peru, Phys. Earth planet. Interiors, 87, 1-2, 33-54, doi: 10.1016/0031-9201(94)90020-5.

Okal, E.A. and Reymond, D. (2003). The mechanism of great Banda Sea earthquake of 1 February 1938: Applying the method of preliminary determination of focal mechanism to a historical event, Earth planet. Sci. Lett., 216, 1-2, 1-15, http://doi.org/10.1016/S0012-821X(03)00475-8.

Okal, E.A. and Borrero, J.C. (2011). The 'tsunami earthquake' of 22 June 1932 in Manzanillo, Mexico: Seismological study and tsunami simulations, Geophys. J. Int., 187, 3, 1443-1459, doi:10.1111/j.1365-246X.2011.05199.x.

Okal, E.A., Synolakis, C.E. and Kalligeris, N. (2011). Tsunami simulations for regional sources in the South China and adjoining seas, Pure appl. Geophys., 168, 6-7, 1153-1173, doi: 10.1007/s00024-010-0230-x.

Okal, E.A., Kirby, S.H. and Kalligeris, N. (2016). The Showa Sanriku earthquake of 02 March 1933: A global seismological reassessment, Geophys. J. Int., 206, 3, 1492-1514, doi: 10.1093/gji/ggw206.

Oncescu, M.-C. and Bonjer, K.-P. (1997). A note on the depth recurrence and strain release of large Vrancea earthquakes, Tectonophysics, 272, 2–4, 291 - 302, http://doi.org/10.1016/S0040-1951(96)00263-6.

Petroy, D.E. and Wiens, D.A. (1989). Historical seismicity and implications for diffuse plate convergence in the northeast Indian Ocean, J. geophys. Res., 94, B9, 12301-12319, http://doi.org/10.1029/JB094iB09p12301.

Priestley, K.F., Baker, C. and Jackson, J.A. (1994). Implications of earthquake focal mechanism data for the active tectonics of the south Caspian Basin and surrounding regions, Geophys. J. Int., 118, 1, 111-114, http://doi.org/10.1111/j.1365-246X.1994.tb04679.x.

Quittmeyer, R.C. and Kafka, A.L. (1984). Constraints on plate motions in southern Pakistan and the northern Arabian Sea from the focal mechanisms of small earthquakes, J. geophys. Res., 89, B4, 2444-2458, http://doi.org/10.1029/jb089ib04p02444.

Quittmeyer, R.C., Kafka, A.L. and Armbruster, J.G. (1984). Focal mechanisms and depths of earthquakes in central Pakistan: A tectonic interpretation, J. geophys. Res., 89, B4, 2459-2470, http://doi.org/10.1029/jb089ib04p02459.

Raeesi, M. and Atakan, K. (2009). On the deformation cycle of a strongly coupled plate interface: The triple earthquakes of 16 March 1963, 15 November 2006, and 13 January 2007 along the Kurile subduction zone, J. geophys. Res., 114, B10, B10301, http://doi.org/10.1029/2008JB006184.

Russo, R.M., Okal, E.A. and Rowley, K.C. (1992). Historical seismicity of the southeastern Caribbean and tectonic implications, Pure appl. Geophys., 139, 1, 87-120, doi: 10.1007/BF00876827.

Singh, S.K. and Wyss, M. (1976). Source parameters of the Orizaba earthquake of August 28, 1973, Geofis. int. 16, 3, 165-184.

Shudofsky, G.N. (1985). Source mechanisms and focal depths of eastern African earthquakes using Rayleigh-wave inversion and body-wave modelling, Geophys. J. R. astr. Soc., 83, 563-614, http://doi.org/10.1111/j.1365-246X.1985.tb04328.x.

Stewart, G.S. and Cohn, S.N. (1979). The 1976 August 16, Mindanao, Philippine earthquake (Ms=7.8) - evidence for a subduction zone south of Mindanao, Geophys. J. R. astr. Soc., 57, 1, 51-65, doi: 10.1111/j.1365-246X.1979.tb03771.x.

Storchak, D.A., Di Giacomo, D., Bondár, I., Engdahl, E.R., Harris, J., Lee, W.H.K., Villaseñor, A. and Bormann, P., (2013). Public release of the ISC-GEM Global Instrumental Earthquake Catalogue (190-2009), *Seismol. Res. Lett.*, 84(5), 810-815, doi: 10.1785/0220130034.

Storchak, D.A., Harris, J., Brown, L., Lieser, K., Shumba, B., Verney, R., Di Giacomo, D., Korger, E. I. M. (2017). Rebuild of the Bulletin of the International Seismological Centre (ISC), part 1: 1964–1979. Geosci. Lett. (2017) 4: 32. doi: 10.1186/s40562-017-0098-z.

Suárez, G. (2000). Reverse faulting in the Isthmus of Tehuantepec: backarc deformation induced by the subduction of the Tehuantepec ridge, in Delgado-Granados, H., Aguirre-Díaz, G.J., Stock, J.M. (eds), Cenozoic tectonics and volcanism of Mexico. Geol. Soc. Am. Special Paper 334, 263-268, http://doi.org/10.1130/0-8137-2334-5.263

Tichelaar, B.W. and Ruff, L.J. (1991). Seismic coupling along the Chilean subduction zone, J. geophys. Res., 96, B7, 11997-12022, doi: 10.1029/91JB00200.

Tsai, V.C., Nettles, M., Ekström, G. and Dziewonski, A.M. (2005). Multiple CMT source analysis of the 2004 Sumatra earthquake, Geophys. Res. Lett., 32, 17, L17304, doi: 10.1029/2005GL023813.

Van Dusen, S.R. and Doser, D.I. (2000). Faulting processes of historic (1917-1962) M >= 6.0 earthquakes along the north-central Caribbean margin, Pure appl. Geophys., 157, 5, 719-736, http://doi.org/10.1007/PL00001115.

Weston, J., Engdahl, E.R., Harris, J., Di Giacomo, D. and Storchak, D.A. (2018). ISC-EHB: Reconstruction of a robust earthquake dataset, Geophys. J. Int., 24, 1, 474-484, doi: 10.1093/gji/ggy155.

Xu, L.-S. and Chen, Y.-T. (1997). Source parameters of the Gonghe, Qinghai Province,

China, earthquake from inversion of digital broadband waveform data, Acta seism. sin., 10, 2, 143-159, http://doi.org/10.1007/s11589-997-0084-1.

Zheng, S-H. and Suzuki, Z. (1993). Moment tensors of earthquakes in and near the Tibetan Plateau and their scaling law, Acta seism. sin., 6, 2, 365-377, http://doi.org/10.1007/BF02650949.

Zhou, H.L., Liu, H. and Kanamori, H. (1983). Source processes of large earthquakes along the Xianshuihe fault in southwestern China, Bull. seism. Soc. Am. 73, 2, 537-551.

Bibliography of publications resulting from the work performed under the award:

Di Giacomo, D., Engdahl, E. R. and Storchak, D.A. (2018). The ISC-GEM Earthquake Catalogue (1904–2014): status after the Extension Project, Earth Syst. Sci. Data, 10, 1877-1899, doi: 10.5194/essd-10-1877-2018

Lentas, K. (2018). Towards routine determination of focal mechanisms obtained from first motion P-wave arrivals, Geophys. J. Int., 212(3), 1665–1686. doi: 10.1093/gji/ggx503

Di Giacomo, D., Engdahl, E. R. and Storchak, D.A. (2018). Comment on "Historical and recent large megathrust earthquakes in Chile" by Ruiz and Madariaga, 2018, Tectonophysics, 745, 453-456, doi: 10.1016/j.tecto.2018.05.016

Lentas, K. & Harris, J. (2019). Enhanced performance of ISC focal mechanism computations as a result of automatic first-motion polarity picking optimization, J. Seismol., 1141-1159, https://doi.org/10.1007/s10950-019-09862-x.

Lentas, K., Di Giacomo, D., Harris, J., and Storchak, D. A. (2019). The ISC Bulletin as a comprehensive source of earthquake source mechanisms, Earth Syst. Sci. Data, 11, 565-578, https://doi.org/10.5194/essd-11-565-2019

Di Giacomo, D. & Dewey, J. (2020). The (Mythical) M 8.2 Off Coast of Peru Earthquake of 12 December 1908, Seism. Res. Lett., 91(1), 488-498, https://doi.org/10.1785/0220190232

Date: July 13, 2020

/D.A. Storchak/